PROCESSING YOUNG PLANTATION-GROWN EUCALYPTUS NITENS FOR SOLID-WOOD PRODUCTS.
2: PREDICTING PRODUCT QUALITY FROM TREE, INCREMENT CORE, DISC, AND 1-M BILLET PROPERTIES

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ABSTRACT

Butt logs of 15 trees of *Eucalyptus nitens* (Dean et Maiden) Maiden, aged 15 years, diameter at breast height 55 cm, were cut into appearance-grade lumber and rotary-peeled and sliced veneer, and the second logs into rotary-peeled veneer. A 1-m billet was removed from between butt and second logs of each tree, as well as discs at successive heights. In addition, breast-height increment cores and breast-height measurements of longitudinal growth strain served to characterise the wood properties and processing, product, and clearwood mechanical properties of each tree. Fibre dimensions, density, and microfibril angle were measured by SilviScan on a sample from height 6 m. Boards were quarter-sawn from the 1-m billet and air- and dehumidifier-dried, and internal checking and shrinkage were measured on these boards and on discs from height 6 m.

"Sawability" variables of the butt log (viz log-end splits, flitch movement off the saw, timber crook, and timber conversion percentage) showed strong intercorrelations with one another and with longitudinal growth strain, measured at breast height on the standing tree. Amounts of internal checking and collapse in the air- and then kiln-dried butt-log boards were strongly correlated with checking measured on discs and on the billet boards. Shrinkage of the 1-m boards and of blocks from the 6-m-height disc was correlated moderately with collapse and checking in the butt-log boards.

Clearwood modulus of elasticity, measured on eight test sticks cut from the billet from height 6–7 m, showed a strong increasing gradient from pith to bark as well as wide variation among trees. Density showed only a small pith to bark increase, while microfibril angle showed a rapid decrease from the pith over the first seven rings. Clearwood modulus of elasticity was moderately correlated with modulus of elasticity of veneer sheets, measured sonically. Tree-mean clearwood modulus of elasticity was strongly correlated with the density/microfibril angle ratio, as was modulus of elasticity of individual test sticks.

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Trees varied strongly in product characteristics and wood properties, and there were strong correlations (a) between breast-height growth strain and sawability characteristics, and (b) between checking and collapse in butt-log boards and tangential shrinkage and checking measured on discs. This indicated possibilities for genetic selection against growth-stress-related sawing problems and internal checking on drying, the two main deficiencies of *E. nitens* for appearance lumber. Good correlations of appearance-lumber and veneer properties with similar traits measured on the standing tree or from cores, discs, and a 1-m billet, indicated that effective evaluation of species, provenances, and individual trees is possible without recourse to full-scale sawing studies.

Keywords: sawing; timber; veneer; individual-tree; disc; billet; growth stress; checking; stiffness; shrinkage; collapse; wood properties; correlation; *Eucalyptus nitens*.

INTRODUCTION

Processing of plantation-grown *Eucalyptus nitens* into solid-wood products has been studied in New Zealand by sawing and rotary-peeling logs from individual trees (McKenzie *et al.* 2003.). Butt logs of 10 trees from a 15-year-old pruned stand, of mean diameter at breast height (dbh) 55 cm, were sawn, the second logs were peeled, and the quality and yield of appearance-grade lumber and of structural veneer were evaluated. For another five trees, both butt logs and second logs were rotary-peeled. The 15 trees varied widely in growth-stress-related sawing problems, yield, and drying defects of appearance-grade timber, especially collapse and internal checking, and in stiffness of rotary-peeled veneer, which was reported by McKenzie *et al.* (2003).

Growth stress, for which eucalypts are noted (Nicholson 1973; Jacobs 1979, p.27; Kubler 1987; Page 1984) causes log end-splitting, distortion of logs and boards on sawing, and brittle heart, and all compromise product recovery. Although growth stress can be assessed by measuring peripheral strain on standing trees (Nicholson 1971; Fournier *et al.* 1994), the necessary removal of bark for multiple samples is destructive on small trees. Investigations into relationships between growth stress and wood properties in eucalypt trees have so far not led to an indirect, less damaging, more cost-effective measure of growth stress (Nicholson *et al.* 1972, 1975; Polge & Thiercelin 1979; Ferrand 1982; Muneri *et al.* 1999; Raymond 2000; Yang & Waugh 2001). The assessment of log end-splitting, which results from growth stress, has not been standardised. In one study several log end-splitting indices were used and all were poor indicators of board splitting, assumed to be a growth-stress-related defect (Garcia & Lima 2000).

A wide range of pre-kiln-drying treatments has been developed for eucalypts to reduce degrade; these include wrapping or coating timber, drying in sheds with restricted airflow, and pre-steaming or pre-drying with fairly constant equilibrium moisture content. All of these add to the cost of processing (Vermass 2000). Timber drying defects are a major concern with young eucalypts (Campbell & Hartley 1984). Collapse is evident when drying leads to corrugations on the wood surface or "washboarding" (Jacobs 1979; Chafe *et al.* 1992; McKenzie *et al.* 2003) which can be partially reversed by additional steam reconditioning. Internal checking is often associated with collapse, which is an "excessive or irregular form of shrinkage during drying, … which occurs above fibre saturation point when liquid is removed by drying from cells. … On the radial face, collapse shows as a 'washboard' or fluted surface and on the tangential or back face it shows as heavy open checks with distortion of the surface as well" (Jacobs 1979). Face checking is also a recognised problem in drying eucalypt timber for appearance grades. Quarter-sawing reduces face checking but checks occur internally. Internal checks may close during reconditioning but the discontinuity remains and constitutes a defect for some end uses. Internal checks can develop in *E. nitens* with air-drying and with mild kiln-drying (Haslett & Young 1992; Yang & Waugh 1996; Shelbourne *et al.* 2002). Curiously, Washusen (2001) reported no internal checking in quarter-sawn 33-year-old *E. nitens* from north-east Victoria.

There is much current interest in the production of solid-wood products from *E. nitens* in Australia, South Africa, New Zealand, and Chile. Several past studies have evaluated growth stress (as microstrain, the change in length of a small strip of outerwood after it is freed from growth stress) and drying defects. McKimm (1985a, b) found differences amongst five provenances of *E. nitens* in growth strain and collapse, which was reported as "severe" before reconditioning; no internal checking was reported. McKimm *et al.* (1988) assessed structural and appearance-grade timber from 20-year-old *E. nitens*, and found internal and face checking varied significantly among trees. Both these studies and that of Yang & Waugh (1996) found timber distortion was within grade standards, but no correlations with growth strain were calculated. Purnell (1988) estimated correlations for log end-splitting and collapse with density and moisture content. The log end-splitting, in addition to radial splits, had a complex pattern of elliptical splits at the heartwood/sapwood boundary. The combined splitting scores showed large among-tree variation and moderate correlations with whole-tree density and whole-tree moisture content. Collapse, which was most pronounced in stump-height and 2.4-m-height samples, was correlated with log end elliptical splits, which were suggested to be collapse-related phenomena. Rozas *et al.* (2001) found drying techniques affected the levels of face and internal checks in *E. nitens*.

Discs were taken at regular height intervals in a New Zealand study of twenty 16-year-old trees of *E. nitens*, and then slowly kiln-dried to evaluate internal checking. This related closely to levels of checking in boards sawn from a basal 1.5-m billet and dried similarly (Lausberg *et al.* 1995 ; Shelbourne *et al.* 2002). Although a standard method of sampling and processing discs of *Pinus radiata* D.Don to assess internal checking has been developed (McConchie & McConchie 2001), there is no generally accepted disc-based method for eucalypts which correlates with internal checking in boards. Checking is a defect that is caused entirely by drying, and both destructive and non-destructive methods of assessing individual trees need to be devised to predict levels to be expected in the dried lumber.

Stiffness of veneer, which is desirable for laminated veneer lumber can be measured through sound velocity by Pundit™ (McKenzie *et al.* 2003; Gaunt *et al.* 2003), and has also shown much tree-to-tree variation. Acoustic tools such as Fakopp™ have been developed to measure stiffness of standing trees (Booker & Sorensson 1999) but the equipment has shown lack of durability in service. In a study of *E. dunnii* Maiden, significant correlations were found between sound velocity, measured by Fakopp™, and timber stiffness for 9-year-old but not 25-year-old trees (Dickson *et al.* 2000). A new acoustic tool is being tested in New Zealand for this purpose (J.Lee pers. comm.).

The Pilodyn™ penetrometer measures the penetration of a spring-loaded pin into the outerwood; this is moderately correlated with outerwood density in *E. nitens* (Gea *et al.*

1997; Raymond & MacDonald 1998) and is a useful predictor of density for populations such as families or stands of trees. Sampling standing trees at breast height by pith-to-bark increment cores of 5, 10, and 12 mm diameter is routinely used for measuring wood properties, including density (Raymond & Muneri 2001; Kube & Raymond 2002a), moisture content, heartwood development, spiral grain, and chemical composition (Treloar & Lausberg 1995). Breast-height outerwood cores can be used for extensive population sampling to predict whole-tree density and other characteristics, provided appropriate predictive regressions have been determined (Downes *et al.* 1997). Detailed intra-ring density information, including earlywood minimum and latewood maximum density, can be obtained from X-ray densitometry on increment cores (Cown & Clement 1983).

Cross-sectional fibre dimensions, wood density, microfibril angle, cellulose crystallite width, and spiral grain can all be measured, ring by ring, with SilviScan™, a wood micro-structure analyser (Evans *et al.* 2000). This can be done from a strip machined from a 12-mm increment core or a disc.

A twin-bladed skillsaw has been developed to take 20 × 20 × 300-mm samples from standing trees for testing for mechanical properties such as stiffness (Booker & Sorensson 1999). Non-destructive methods have yet to be developed for assessing internal checking, which results from various methods of drying. However, there are possibilities for relating checking to shrinkage and collapse, which can, in turn, be determined from increment cores. Both have recently been measured successfully on 12-mm increment cores (Kube & Raymond 2002a; C.Raymond pers. comm.). Use of ultrasound for this purpose has been investigated unsuccessfully (Booker 1995).

Determining within-tree variation of important attributes is necessary in order to define, *inter alia*, appropriate sampling strategies for predicting whole-tree values. Discs, or small billets, taken at regular height intervals up the stem, can be used to provide material for measuring various wood and end-product properties, to predict whole-tree values. This has been done for wood, chemistry, pulping, fibre, and handsheet properties that are important for kraft and chemi-mechanical pulping (Downes *et al.* 1997; Kibblewhite *et al.* 1998; Jones & Richardson 1999; Kibblewhite & Riddell 2000; Kibblewhite & Shelbourne 1997). The important wood properties for solid-wood uses and product properties themselves need to be similarly studied to determine the relationships between disc, billet, and whole-tree properties for different eucalypt species (Raymond 2000).

Economical methods of predicting quality and yield of solid-wood products, suitable for evaluating different species and populations, are needed. Large numbers of individual trees also need to be assessed non-destructively and cheaply in breeding to improve solid-wood product quality. For most scenarios the costs of full-scale sawing studies are prohibitive. Relationships of wood properties of individual trees with the characteristics of their sawn timber and veneer were therefore studied to see if it was possible to predict lumber quality from core, disc, and short billet sampling. The same 15 trees of *E. nitens* that were processed for appearance-grade lumber and veneers (McKenzie *et al.* 2003), were also sampled for wood properties, mechanical properties, and drying properties by increment cores, discs at various heights, and boards cut from a 1-m billet between butt and second logs. These characteristics will be evaluated and related to the characteristics of sawn timber and veneers of the same trees in this paper, with the object of discovering predictive relationships that can be utilised in other research.

MATERIAL AND METHODS

Tree Selection

The stand of *E. nitens* utilised for this study was planted in 1983, in Golden Downs Forest, Nelson (long. 172°48´E, lat. 41°24´S) at an altitude of 230 m (McKenzie *et al.* 2003). The *E. nitens* were thinned progressively from an initial stocking of 833 stems/ha to 100 stems/ha by age 6 years. Pruning was done in four lifts to 8 m by age 6 years. In 1998, at age 15 years, the 15 trees to be felled and processed were selected from 40 for a range of outerwood density.

Tree and Log Assessment

Longitudinal growth stress, as tensile microstrain, was measured on the 15 selected standing trees in two diametrically opposed positions at breast height by the simplified version of the Nicholson (1971) method. This entailed creating a bark window without damaging the wood, gluing two metal discs on to the wood, and measuring the distance between them with a strain gauge before and after releasing tension by cutting the wood above and below the discs.

Diameter at breast height 1.4 m (dbh), total tree height, and height to first branch were measured, and 1.4 m height and north were marked on each stem.

After felling, a 5.5-m butt log, a 1-m billet, and then a 5.5-m second log as well as intervening discs were cut from each tree (Fig. 1). Length, diameters at large end (l.e.d.) and small end (s.e.d.), and presence of decay were recorded for each sawlog. The radial extent of log end-splits was assessed, immediately before sawing or peeling, as the summed length-of-split/log-diameter ratio for all splits, giving the “log splitting index” at each log end. The diameters of the largest branch stub in the four quadrants of each peeler log were averaged to give “branch index” (BIX).

Stiffness or modulus of elasticity (MoE) was assessed in each tree by measuring sound velocity with a Fakopp™ device (Booker & Sorensson 1999). Transducers were placed 1 m apart on the tree, with the bottom transducer approximately 0.5 m above the ground. Three transit times were taken at each of two quadrants of the standing tree and averaged.

A Pilodyn penetrometer (Klitscher *et al.* 1995) was used to take two readings at breast height to predict wood density. A 5-mm pith-to-bark core (for density determination) was removed from the region between the Pilodyn sample points.

Sawing

Each pruned butt log, cut to 5 m length, was sawn to maximise production of 40-mm-thick quarter-sawn timber, with the residue as 25-mm boards. For details of the sawing and drying of the 5-m boards and their assessment for crook, internal and face checking, collapse, and recovery *see* McKenzie *et al.* (2003).

1-m Billet Samples

One-metre billets were taken at height 6–7 m from all trees and were sawn to produce a single 50-mm diametral plank on the north-south axis of each tree, and four 25-mm

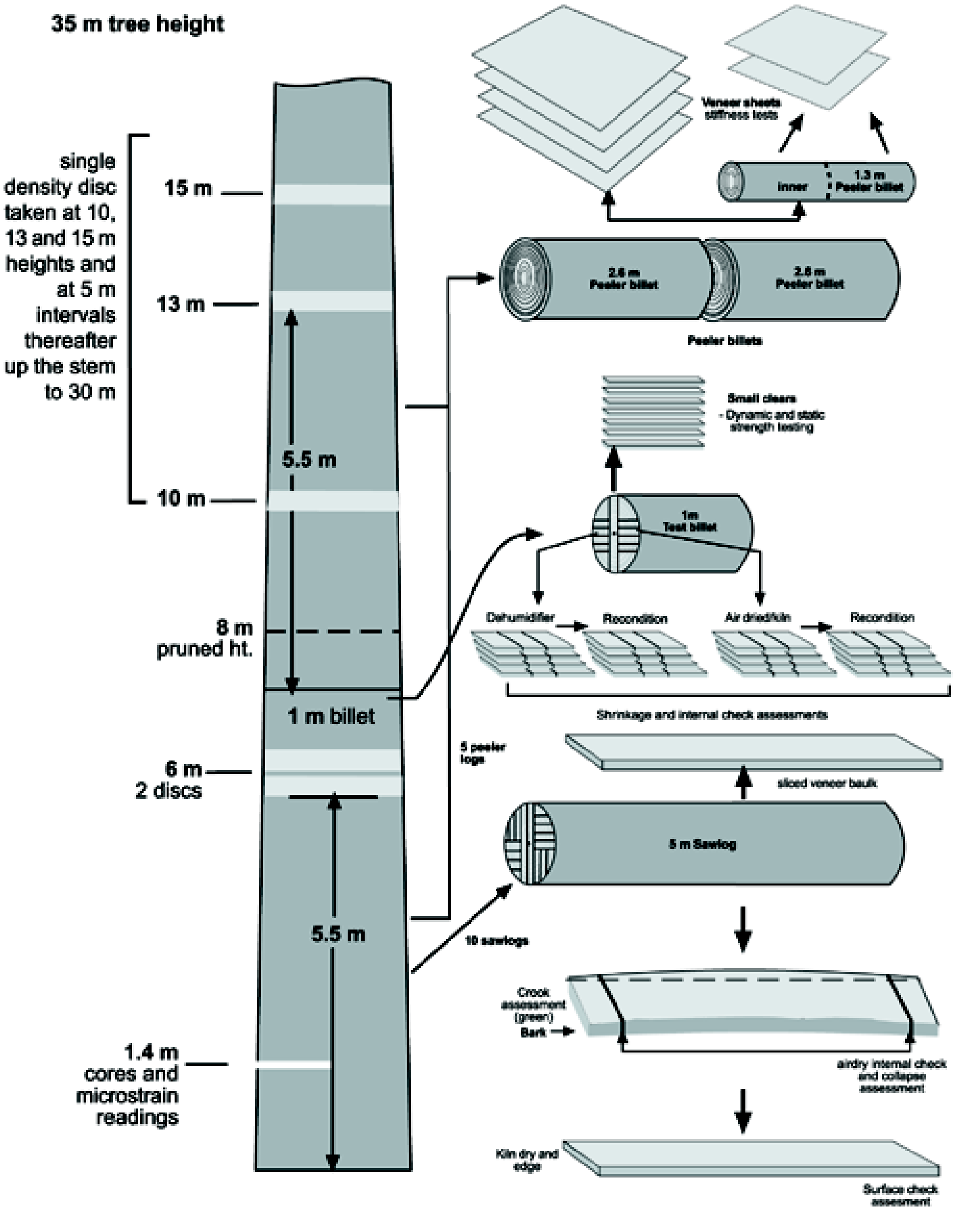

FIG. 1–Position of samples in relation to tree height and processing of logs and billets

boards, quarter-sawn from each flitch (Fig.2). Tree 24 had very severe log end-splitting and could not be sawn to produce the required boards. Cross-sectional dimensions of each of the eight green quarter-sawn boards were measured with callipers at "shrinkage points" marked on the sides, top, and bottom of each board. A dehumidifier was used to give slow controlled-drying of four boards per tree, two from each side of the billet, at 30°C to 18% m.c. (an equipment failure led to the temperature rising to 50°C, possibly for over

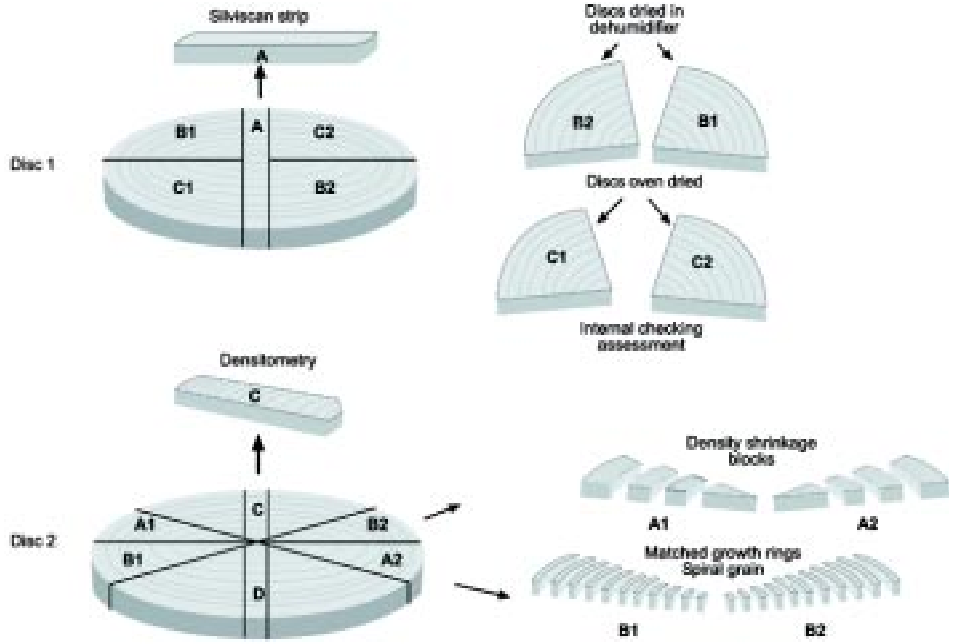

FIG. 2–Samples taken from Discs 1 and 2 at 6 m tree height

50 hours) and then to 12% equilibrium moisture content (e.m.c.). The other four boards per tree were air-dried and then kiln-dried with the butt-log boards (McKenzie *et al.* 2003).

The cross-sectional dimensions of each board were remeasured at the same four shrinkage points. Then the half-boards with the shrinkage points were cut off and reconditioned by steaming for either 4 hours (dehumidifier-dried boards) or 2 hours (air-dried boards), and returned to 12% e.m.c. The dimensions were remeasured to give cross-sectional area and to calculate shrinkage percentage after reconditioning.

Each of the 16 half-boards per tree was then cross-cut at four points and the number of internal checks was recorded for each ring. Mean checking scores were obtained for each tree as checks per millimetre of ring circumference (from board thickness), but only in Rings 4 to 12. The percentage of these rings affected by checking was also calculated.

The diametral plank was ripped into four planks of equal width from either side of the pith. These too were air-dried for 2 months prior to the machining of 20 × 20-mm clear test specimens (“sticks”) from the outer edge of each plank. Thus, the outermost stick came from outermost rings of the billet while the innermost stick came from approximately 40 mm outside the pith. The test sticks were air dried to 12% e.m.c., and tested using BS 373:1957. These sticks were then assessed for modulus of rupture or strength (MoR), for modulus of elasticity or stiffness (MoE), both by static bending, and for compression strength parallel to grain, shear strength parallel to grain, and Janka hardness. After testing, the sticks were oven-dried, and their moisture contents and basic and nominal densities were derived. The method used here of testing sticks from height 6 m differs from the normal practice of taking samples at breast height.

Disc and Core Samples

Discs from height 6 m

The following additional variables were assessed on all 15 trees from discs sampled at 6 m tree height :

- A pith-to-bark strip from each tree (from the first 6-m disc, Fig. 2) was assessed by SilviScan2 (Evans & Ilic 2000) for wood density, percentage vessels, radial and tangential fibre diameter, wall thickness, microfibril angle (MFA), and density (air-dry).
- Internal checking was assessed from the four sectors of the first disc. Two sectors from opposite sides of the disc were oven-dried and the other two sectors were dried in the dehumidifier with the billet boards. The four sectors were then sawn tangentially to expose checks. Each ring's circumference was calculated using radius measurements to midpoints of each ring, derived from the densitometry data from height 6 m. Numbers of checks were recorded by ring and expressed as checks per millimetre of ring circumference. Mean checks per metre for the two sectors that were oven- *vs* dehumidifier-dried were obtained for each tree. Heartwood, transition, and sapwood rings were not distinguished in this study.
- Shrinkage was then assessed in three blocks, cut tangentially from the second 6-m green disc, from opposite quadrants, to include Rings (numbered from the pith outwards) 1–5, Rings 6–10, and the remaining rings (Fig. 2). Radial, longitudinal, and tangential dimensions were measured on green blocks and measurement points were marked. The blocks were air-dried, and measured when they reached 12% m. c. They were then reconditioned, returned to 12% m.c., and remeasured. Radial, tangential, longitudinal, and volumetric shrinkages were calculated from the green condition (gross shrinkage), and after reconditioning.
- Density changes from pith to bark were measured by X-ray densitometry on a radial strip cut from the second 6-m-height disc (Cown & Clement 1983).
- Spiral grain was assessed in alternate rings, from Rings 2 to 14, in two opposing sectors of wood in the second disc by the method of Harris (1989).

Breast-height core samples

The outerwood basic density of each tree was assessed from the outer five rings of a breast-height pith-to-bark 5-mm increment core. Latewood and earlywood basic density was assessed for all rings on the same core by X-ray densitometry (Cown & Clement 1983).

Discs sampled over length of stem

Diameter under bark and basic density (Smith 1954) were measured on discs cut at stump height, and then at heights 6, 10, 13, 15, 20, 25, 30 m (tree height permitting). Whole-tree density was calculated from mean density for each stem section, weighted by volume.

Veneer Peeling and Drying, and Assessment of Veneer Sheets

Butt logs of five of the study trees and all second logs from height 7–12 m were rotary-peeled for veneer. For details of veneer peeling and drying, and assessment of the veneer sheets for stiffness, *see* McKenzie *et al.* (2003).

Statistical Analysis

Product characteristics (reported by McKenzie *et al.* 2003) and tree, core, disc, and billet sample characteristics were grouped into four categories: 1 – Those related to growth stress, splitting, and distortion; 2 – Internal checking characteristics; 3 – Shrinkage-related characteristics; 4 – Wood microstructure, density, and mechanical properties.

Tree means, coefficients of variation (CV%) among tree means, and minima and maxima were obtained for each characteristic. Correlations were also calculated within trees and among tree means for different characteristics in the four categories. Variance-component analysis with the SAS procedure MIXED (SAS Institute Inc. 1989) was used to quantify the among- and within-tree variance of a number of properties. Where appropriate, fixed effects were included — for example, to account for drying treatments.

For some properties, a simple among- and within-tree analysis was performed. Properties analysed in this way were growth strain (two measurements per tree), timber crook (measured on an average of 20 sawn boards per tree from the butt log), and breast-height outerwood density (mean over four cores per tree).

Other properties were analysed using more complex models (variance components were estimated for each analysis) :

- Butt- and second-log log-splitting measurements were analysed together using a mixed model, with log height class specified as a fixed effect, and among- and within-tree variances estimated as random effects.
- Shrinkage percentage in 1-m boards (eight measurements per tree) was analysed using a mixed model, with drying treatment specified as a fixed effect, and among- and within-tree variances estimated as random effects.
- Tree mean values for each mechanical property are unweighted means of eight test sticks per tree (derived from the 1-m billet), adjusted for missing samples where necessary. Clearwood modulus of elasticity of test sticks was analysed using a mixed model, with radial distance of the eight test sticks from the centre of the log specified as a fixed covariate, and tree, sample(tree), and sub-sample (sample(tree)) as random effects.
- Checks in 1-m boards (a total of 16 half-boards/tree × 4 cuts per board) were analysed using a mixed model, with "drying treatment" specified as a fixed effect and "tree", "board within (tree)", and "cut within (board × tree)" specified as random effects. Face checks in butt-log boards were analysed using a nested model, with "tree", "board within (tree)", and "piece within (board × tree)" (usually two per board) specified as random effects.

Repeatability was calculated as the ratio of the variance between trees to the total variance of tree means. For example, for properties with two nested levels of within-tree variance, the following formula was used:

$$\mathit{repeatability} = \frac{\sigma_t^2}{\sigma_t^2 + \sigma_{w1}^2 / n_1 \; \sigma_{w2}^2 / (n_1 \, n_2)}$$

where σ_t^2 is the variance between trees, σ_{w1}^2 and σ_{w2}^2 are the first and second nested within-tree variances, and n_1 and n_2 are the number of samples at each nested level of sampling. Where sample sizes were unbalanced, harmonic means were used for calculating the values of n.

Analyses of variation among trees and among rings for number of checks per metre of ring and for densitometry ring density values were undertaken for the sectors within the 6-m disc and for the four boards in each 1-m billet. Two-way analyses of variance (ANOVAs), with factors “tree” and “ring”, were used to test for differences between rings, the rings being tested against the ring × tree interaction term. Differences between means of number of checks and in mean collapse score between small and large ends of the 5.5-m logs, were also analysed using paired t-tests.

Analysis of covariance of veneer sheet stiffness, adjusting for the effect of individual-tree stem diameter at point of peeling and of height of billet up the stem, was undertaken by fitting linear, quadratic, and cubic terms in diameter. This analysis, which included all veneer sheets from the butt logs and upper and lower second-log billets, also provided least-squares estimates of tree-mean veneer stiffness, adjusted for wood age and log height.

An analysis of variance of the individual test stick data for modulus of elasticity, modulus of rupture, shear strength tangential and radial, compression strength, and hardness was undertaken, to reveal the proportions of total variation between trees, between radial positions from pith to bark, and within each radial position, from opposite sides of the pith. Variance components were again calculated using SAS PROC MIXED.

Multiple regression (using SAS PROC REG as well as simple correlation) was used to explore some relationships, particularly the prediction of modulus of elasticity from density and microfibril angle from SilviScan data. Further analyses were used to examine among-tree variation in modulus of elasticity. ANOVAs were used to analyse the significance of height on these characteristics as well as to generate variance component estimates using SAS PROC MIXED.

Shrinkage of 1-m boards was measured in cross-sectional area (width × thickness). ANOVA was used to test for the effects of drying treatment and reconditioning on shrinkage of boards and to generate variance components for repeatability estimation using SAS PROC MIXED.

Disc shrinkage measurements were obtained in groups of five rings, i.e., Rings 1–5, 6–10, and 11–15. ANOVAs were performed to test for differences between ring groups, and for the effect of reconditioning. The effects of the two drying methods (air/kiln *vs* dehumidifier) and two reconditioning methods (steam bath *vs* kiln steaming) on checking in the 1-m boards were compared using ANOVA. This ANOVA included the following fixed effects: tree, drying method, reconditioning, drying method × reconditioning. The drying method was tested against the board (tree) mean square, while the reconditioning was tested against the board (tree) × reconditioning mean square.

Correlations between the different methods of assessing basic density and disc densities from different heights with tree mean density were also calculated.

RESULTS AND DISCUSSION

Variation Within and Among Trees

Growth stress and related log and timber properties

There was wide variation between trees in average tensile microstrain resulting from longitudinal tension in the outer rings (minimum 205, maximum 1685, CV 69% for an overall mean of 537) (Table 1) but there was also extreme variation between the readings of microstrain taken on opposite sides of the tree (not tabulated). This may partly reflect the occurrence of tension wood, an important cause of high growth stresses in hardwoods (Kubler 1987), as well as the inherently high variability of longitudinal growth stress. More than two measurements of microstrain were evidently needed to characterise individual-tree values sufficiently precisely, though the highest value may be critical in determining sawing problems. Despite this, the repeatability of tree means for this trait (ratio of variance between trees/variance within trees) was still 82% (Table 2). There was similar wide variation between trees and high repeatability of log end-splitting and timber crook, and in flitch movement off the saw (spring) and timber conversion (McKenzie *et al.* 2003).

TABLE 1–Individual-tree variation in growth-stress and related log and timber characteristics

	Butt log end-splitting (index)	Second log end-splitting (index)	Flitch movement (mm)	Log timber conversion (%)	Timber crook (mm)	Breast height growth strain (tensile microstrain)
Minimum	0.5	1.0	1	37.1	26.5	205
Maximum	5.0	5.0	170	55.9	93.4	1685
Mean	3.00	2.75	81.1	50.1	42.1	537
CV	45.1	41.1	61.7	11.6	48.1	68.7

TABLE 2–Estimates of sampling variance and repeatability of tree means of some sub-sampled properties

Property (type of material)	Estimated variance components		Repeat-ability (%)	p-value
	Among-tree	Within-tree		
No. of checks / m of ring circumference (height 6–7 m boards)	41.0	18.0; 19.9*	93	<0.0001
Presence of checks (height 6–7 m boards)	0.0780	0.0691; 0.0938*	87	<0.0001
Total length of face checks (butt-log boards)	0.0059	0.0041; 0.0092†	93	<0.0001
Microstrain at breast height	111 368	48 633	82	0.0016
Log end-splitting index (butt-log)	1.28	0.27	91	<0.0001
Timber crook (butt-log boards)	398	161	97	<0.0001
Outerwood density (6-m-height discs)	856	386	90	<0.0001
Clearwood MoE (height 6–7 m)	0.653	0.082; 1.046‡	78	0.0046
Cross-sectional area shrinkage (height 6–7 m boards)	3.26	2.16	92	<0.0001
Grain angle (height 6 m)	0.76	4.23, 5.76§	23	0.32

* variance among boards; variance among cuts within boards
† variance among boards; variance among pieces within boards
‡ variance among samples ; variance among sub-samples within samples
§ variance among samples; variance among rings within samples.

Checking

Amount of internal checking (Tables 2, 3) measured in 1-m dehumidifier-dried and air-+kiln-dried boards from the 1-m billet was highly variable among trees, as it was in the butt log (Table 4 of McKenzie *et al.* 2003). In dehumidifier-dried boards, this varied from near 0 for Trees 89 and 86, to 32.8 checks/m of ring for Tree 22. About half the number of checks per metre of ring were found in the air-+kiln-dried boards that were found in the dehumidifier-dried. Repeatability of tree means (across the dehumidifier- and kiln-dried treatments) for checks per metre of ring (based on a total of 16 half-boards and four cuts per board) was high (93%), and also for presence of checking (87%) (Table 2). After steam reconditioning, the amount of checking observable was about the same for the air-+kiln-dried boards, but it reduced from 5.5 to 3.0 checks/m of ring for dehumidifier-dried boards, probably as a result of being reconditioned for twice as long.

Checking was twice as frequent in the oven-dried discs as in the dehumidifier-dried (Table 3). There was large variation between individual tree values for dehumidifier-dried material; six trees out of 14 showed less than 0.6 checks/m of ring while the others ranged up to 31 checks. A comparison of development of checking from pith to bark in dehumidifier- and oven-dried discs and in 1-m boards is shown in Fig. 3. Oven-dried discs showed much larger (apparently erratic) numbers of checks per metre of ring than the other methods, and even the dehumidifier-dried discs seemed to have an exaggerated amount of checking compared to that in 1-m boards. Analysis of variance of number of checks per metre of ring circumference from each method showed no significant difference in checking scores between ring positions for the 1-m boards ($F_{8,104} = 1.09$, p = 0.4), while the disc values differed significantly between rings ($F_{13,168} = 2.56$, p = 0.003 for dehumidifier drying). Checking in dehumidifier-dried discs reached “normal” levels from Ring 3 outwards (heartwood), and highest values in Rings 10–12 (transitional heartwood/sapwood), decreasing in the outer two rings (sapwood).

TABLE 3–Individual-tree variation in internal checking before steam reconditioning (checks per metre of ring circumference) in boards from 1-m billets and in discs, from height 6 m

	1-m boards		Discs	
	Dehumidifier-dried	Air- + kiln-dried	Oven-dried	Dehumidifier-dried
Minimum	0	0	1.8	0
Maximum	32.8	20.2	25.4	31.3
Mean	6.8	3.4	11.2	5.5
CV%	118.5	161.4	61.6	154.9

Shrinkage

There was large variation between trees in radial (4–10%) and tangential shrinkage (10–19%) (Table 4), though longitudinal shrinkage was negligible. Tree-mean cross-sectional area shrinkage (which included collapse) in dehumidifier-dried 1-m boards (Table 4) averaged 14%, ranging from 12% to 21%, and repeatability among trees was 92% (Table 2). The highest shrinkage was for Tree 22, which also showed extremely severe checking. However, Tree 35, which had severe checking, shrank only 12.1% (not

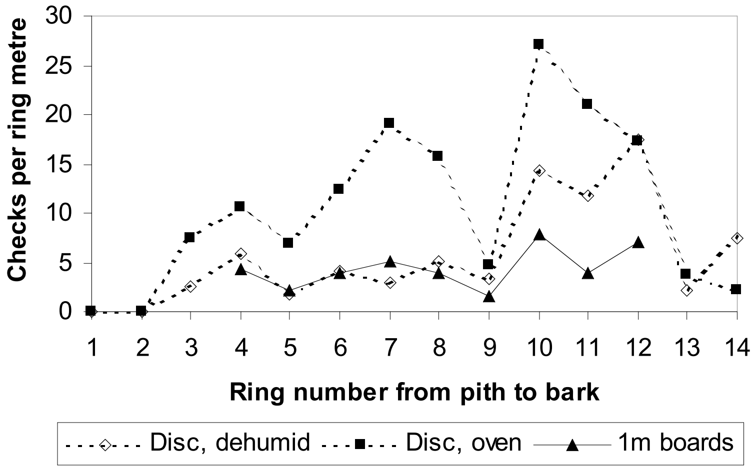

FIG. 3–Distribution of checking by ring number
Note: 5% LSD for comparing ring means are — 9.1, dehumidifier disc; 10.1, oven-dried disc; 5.5, 1-m boards.

tabulated). The shrinkage assessment was based on single shrinkage points, which often missed rings that had shrunk severely ("collapsed"). An improved method of assessment of ring shrinkage should be developed in future studies.

Shrinkage (including some collapse) of air-+kiln-dried boards averaged 11%, significantly less than the 14% of dehumidifier-dried boards ($F_{1,97} = 40$, $p < 0.0001$). This may be attributed to the accidental high temperature in the dehumidifier. Shrinkage of dehumidifier-dried boards that were reconditioned in a steam bath for 4 hours was significantly reduced to 9.6% ($F_{1,110} = 280$, $p < 0.0001$) but reconditioning the kiln-dried boards for 2 hours had little effect on cross-sectional area shrinkage (Table 4). Although the amount of cross-sectional area shrinkage after reconditioning did not differ significantly between the two drying treatments, collapsed rings were observed in some air- +kiln-dried/ kiln-reconditioned boards but not in the dehumidifier-dried/steam bath-reconditioned boards. The persistence of collapse after kiln reconditioning may be due to reconditioning for only half the recommended time (2 hours/25 mm thickness (Haslett 1988)).

Shrinkage plus collapse, measured on blocks cut from height 6 m discs (Table 5), showed much higher values in Rings 11–15 than in Rings 1–5 for both tangential (13.3% *vs* 7.1%) and radial shrinkage (6.4% *vs* 2%) ($F_{2,28} = 58$, $p < 0.0001$ for tangential shrinkage; $F_{2,28} = 120$, $p < 0.0001$ for radial shrinkage). Steam reconditioning resulted in recovery of almost half the tangential and radial shrinkage in the outer-ring samples and a lesser recovery in the Ring 1–5 samples ($F_{1,42} = 132$, $p < 0.0001$ for tangential shrinkage and $F_{1,42} = 69$, $p < 0.0001$ for radial shrinkage) (Table 5).

Density

As could be expected from the choice of the study trees based on outerwood core density, whole-tree basic density ranged widely from 459 kg/m^3 to 546 kg/m^3 (mean 495 kg/m^3, CV 6.2%) (Table 6). Density showed a net increase with height, typical of the

TABLE 4–Individual-tree variation in shrinkage in boards from 1-m billets and in disc blocks from height 6 m

	1-m boards: areal shrinkage (%)				Disc block shrinkage (%) before reconditioning					
	Dehumidifier-dried		Air- +kiln-dried		Rings 11–15			Rings 1–5		
	Dried	Reconditioned	Dried	Reconditioned	Longitudinal	Tangential	Radial	Longitudinal	Tangential	Radial
Minimum	11.9	7.8	9.0	8.3	–0.3	9.8	3.7	–0.1	5	1.4
Maximum	21.1	12.1	15.1	13.5	0.2	19.3	9.6	0.2	9.3	2.5
Mean	14.0	9.6	10.9	10.2	0.04	13.3	6.4	0.05	7.1	2.0
CV	17.6	14.9	13.4	12.9	295.8	22.9	29.6	227.2	17.7	16.2

TABLE 6–Variation in disc density (kg/m^3) with height (m) and correlations with whole-tree density

Variable	Whole tree	Outer-wood core (bh)	0	6	10	13	15	20	25	30
Mean disc basic density	496	498	497	475	494	506	495	520	551	572
Maximum density	546									
Minimum density	459									
Correlation		0.85	0.96	0.95	0.96	0.86	0.90	0.95	0.65	0.76

TABLE 5–Overall mean disc block shrinkage (12% m.c.)

Ring group	Longitudinal shrinkage (%)		Tangential shrinkage (%)		Radial shrinkage (%)	
	Before recond.	After recond.	Before recond.	After recond.	Before recond.	After recond.
1–5	0.05	–0.02	7.1	4.7	2.0	1.7
6–10	0.05	–0.04	9.1	6.2	2.9	2.1
11–15	0.04	–0.02	13.3	7.8	6.4	3.5
5%LSD*	0.07, 0.05		1.5, 0.8		0.7, 0.4	

* Use first value for comparing ring groups and second value for testing effect of reconditioning.

species (Lausberg *et al.* 1995; Raymond & Muneri 2001; Kube *et al.* 2001) but decreased from the base (497 kg/m^3) to 6 m up the tree, and then increased to 572 kg/m^3 at height 30 m. Correlations between whole-tree density and disc values at increasing heights remained high (over 0.90) from the base up to height 20 m, and then decreased. There was a smaller increase in density from pith to bark, with an initial drop to Ring 4, as shown by the densitometric mean values from height 6-m samples of 15 trees (Fig. 4, 5). Pilodyn™ pin penetration (mm) at breast height (not tabulated) correlates moderately (–0.65) with whole-tree density but would be unreliable for measurement of individual-tree density.

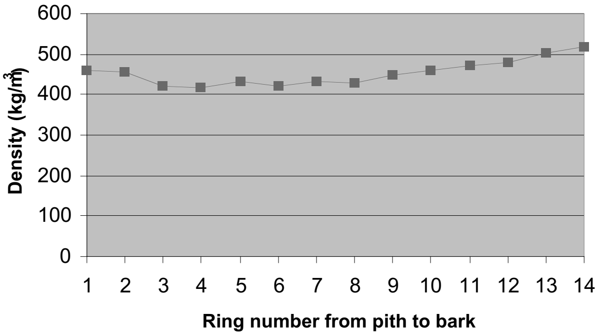

FIG. 4–Average trend in density from pith to bark (15 trees measured by densitometer at height 6 m) Note: 5% LSD = 27.6

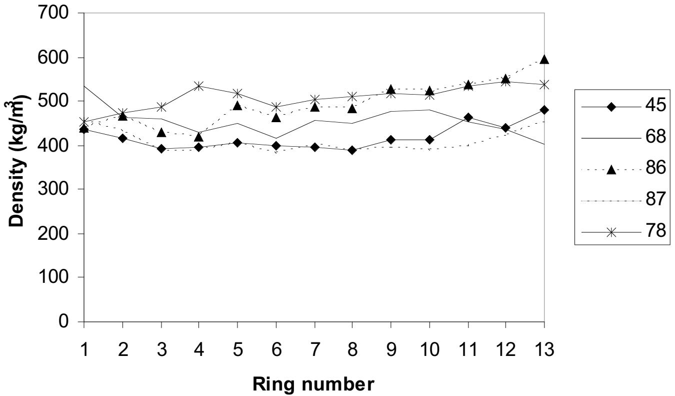

FIG. 5–Individual-tree radial trends in wood density from pith to bark (from densitometry at height 6 m)

Spiral grain

Average mean spiral grain angle across all trees (not tabulated), measured in the 6-m disc, was –2.78° (CV 65%), varying among trees from –0.68° to –7.14°. Spiral grain angle did not vary appreciably from ring to ring, averaging –2.1° in Ring 8 to –3.5° in Ring 4. Twist in boards was negligible in this study, which accords with the low spiral grain angles.

Mechanical properties

Mechanical properties, modulus of elasticity, modulus of rupture, shear strength parallel to grain (radial and tangential), compression strength, and hardness were measured at height 6–7 m (Table 7). Tree mean modulus of elasticity ranged from 7.7 to 11.2 GPa and repeatability was only 78%, reflecting large within-tree variation (Table 2). Trees varied in mean modulus of elasticity from 7.5 GPa near the pith to 12.1 GPa at the bark (Table 8, Fig. 6). The gradient in modulus of elasticity from pith to bark in relation to radial distance is curvilinear but when modulus of elasticity is plotted against ring number (Fig. 6), the gradient is approximately linear. Similar variation among trees and a similar gradient from pith to bark was found in modulus of rupture, compression strength, and hardness, and trees ranked very similarly to modulus of elasticity. There were no clear pith-to-bark trends in tangential and radial shear strength.

Values of mechanical properties (Tables 7 and 8) are shown at an average equilibrium moisture content of 14.2%. Adjustment to 12% e.m.c. raises the mean modulus of elasticity of all trees from 9.50 to 9.90 GPa. The sampling position at height 6–7 m was different from the standard sampling position of breast height because of experimental requirements. This

TABLE 7–Individual-tree variation in mean clearwood mechanical properties (height 6–7 m)

Statistic	MoE (GPa)	MoR (MPa)	Shear strength (MPa)		Compression strength parallel to grain (MPa)	Hardness (N)
			Tangential	Radial		
Minimum	7.7	77.4	8.4	10.9	32.4	3294
Maximum	11.2	102.4	12.3	15.9	47.3	5020
Mean	9.5	88.0	9.7	12.7	39.1	4160
CV%	10.9	9.8	1.0	1.6	4.0	12.5

TABLE 8–Radial variation in overall mean mechanical properties by equidistant position, from pith to bark

Property	Radial positions			
	1	2	3	4
MoE (GPa)	7.49	9.00	9.49	12.06
MoR (MPa)	72.3	85.1	89.2	105.8
Shear (tangential) (MPa)	10.34	9.62	8.97	10.01
Shear (radial) (MPa)	13.1	13.2	12.3	12.5
Compression (MPa)	36.8	36.8	37.7	45.4
Hardness (N)	3673	3923	4014	5043

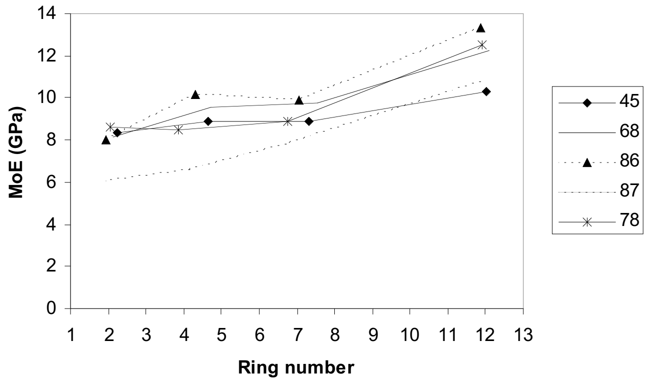

FIG. 6–Radial trends in clearwood modulus of elasticity (height 6–7 m) from pith to bark for five selected trees

was also used by McKinley *et al.* (2002) for ten 11-year-old trees from Northland, which had a modulus of elasticity of 8.95 GPa. Modulus of elasticity of 15- and 11-year-old material differed little from the mean 10.1 GPa MoE (at breast height) for 30-year-old trees from Glentunnel, South Island (Bier 1999). Mean values for compression strength, shear strength, and hardness of 15-year-old material were much lower than for the 30-year-old.

Fibre cross-sectional dimensions, density, and microfibril angle

Mean tree microfibril angle varied from 13.0° to 18.0° (Table 9). Tree-mean fibre wall thickness varied from 1.39 to 1.72 µm, corresponding to lowest and highest density trees. Ranges of tree-mean fibre diameters, radial and tangential, were quite low (12.6–14.4 and 12.1–13.8 µm, respectively) and were unrelated to density. These wood properties were measured in the hope that one or more might be predictive of end-product characteristics such as checking, growth-stress-related sawability problems, and mechanical properties such as stiffness. There were substantial changes in all of these characteristics from pith to bark (e.g., microfibril angle Fig. 7). Microfibril angle decreased quickly from the innermost ring to about Ring 4, and then decreased more slowly to reach lowest values at the bark.

TABLE 9–Individual-tree variation in mean cross-sectional fibre dimensions, microfibril angle, and density

Statistic	Microfibril angle (%)	Wall thickness (µm)	Radial diameter (µm)	Tangential diameter (µm)	Vessels (%)	Density (air-dried) (kg/m^3)
Minimum	13	1.39	12.6	12.1	3.49	534
Maximum	18	1.72	14.4	13.8	6.66	677
Mean	15.0	1.52	13.3	12.7	4.88	591
CV%	10.8	6.7	4.6	3.7	18.9	7.8

Relationships Among Wood, Processing, and Product Characteristics

The main objective of this study was to develop ways of predicting individual-tree means for “sawability” of logs and quality and recovery of sawn timber and veneer, as

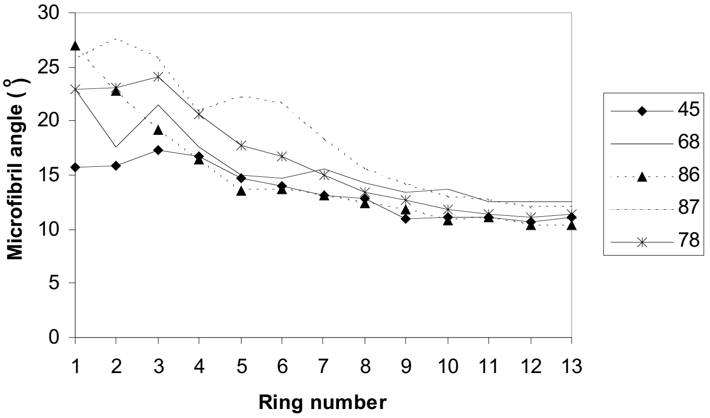

FIG. 7–Radial trends in microfibril angle from pith to bark at height 6 m for five selected trees

reported by McKenzie *et al.* (2003). This was attempted non-destructively, through increment cores and microstrain and sound-velocity measurements on standing trees, and destructively by disc- and short-billet sampling. The high among-tree variability in various characteristics of butt-log boards, veneers, 1-m-billet boards, and of discs taken at different heights offers the possibility of deriving predictive relationships among these characteristics, particularly from wood to product, which will now be examined, mainly through correlation matrices. Because the 15 sample trees were not a random sample of the population with respect to basic wood density (trees were selected to cover the full range of density), correlations among density-related variables are more appropriately referred to as R not r, R^2 being the coefficient of determination.

Correlations between two tree-mean properties are determined partly by their respective repeatabilities, which reflect “determination noise”. The underlying correlation can be estimated by dividing the estimated R by the square root of the product of the two repeatabilities, such that a high “average” repeatability will have little effect on the correlation whereas a low average repeatability will increase the underlying correlation. Repeatabilities of all variables in this study except growth strain (82%), clearwood modulus of elasticity (78%), and grain angle (23%) were all above 87%.

Correlations amongst growth-stress-related characteristics

Correlations among microstrain, butt-log splitting index, bow, crook, and log conversion percentage are shown in Table 10. These processing characteristics of the butt log are all moderately to strongly correlated with microstrain (0.65–0.98), indicating that growth stress is deeply implicated in the sawability problems in this species. End-splitting of logs, the amount of flitch movement from the saw in the first saw-cut (spring), the crook that developed in quarter-sawn boards, and the resulting losses in conversion were all correlated with the amount of growth stress. The high variability between trees in growth stress (Table 1) suggests selective breeding could improve sawability, assuming that the trait is heritable. Tension wood is known to cause high longitudinal growth stresses in the external growth rings (Kubler 1987) and to be associated with high cellulose content. Cellulose content is highly heritable in young *E. nitens* (Kube *et al.* 2001) and cellulose crystallite

TABLE 10–Correlations among tree-mean microstrain, log end-splitting index, distortion of boards, and veneer splitting

Variable	Micro-strain†	Butt log end-splitting index	Second log end-splitting index	Flitch move-ment	Timber crook	Log conversion	Veneer split length
Butt log end-splitting	0.65 **						
Second log end-splitting	0.77 **	0.83 **					
Flitch movement	0.77 **	0.79 **	0.75 **				
Timber crook	0.98 **	0.78 **	0.89 **	0.83 **			
Log conversion	–0.79 **	–0.80 **	–0.82 **	–0.80 **	–0.87 **		
Veneer split length	–0.19	–0.04	–0.22	–0.12	–0.07	0.32	
Veneer split count ‡	0.39	0.49	0.34	0.02	0.35	0.07	0.58 *

* significant at p = 0.05
** significant at p = 0.01
† microstrain is mean of two measurements per tree
‡ number of sheets with more than five end-splits

width, can be measured by SilviScan (Washusen & Evans 2001). However, the relationship of tension wood development, growth stress, and cellulose content, and the heritability of all components are still to be determined.

In contrast to log end-splitting, veneer splitting was not significantly correlated with growth strain (Table 10). However, some veneer splitting may have resulted from uneven heating of logs of five trees which had not been fully submerged in the hot water bath before peeling. A one-way analysis of variance suggested that splitting was indeed significantly worse for these logs. The proportion of veneer edges with more than five splits was 67% *vs* 45% in the fully submerged logs ($F_{1,12} = 5.9$, $p = 0.03$), while mean longest split per sheet was 363 mm *vs* 265 mm ($F_{1,12} = 4.0$, $p = 0.07$). The partial correlation coefficient between growth strain and percentage of veneer edges with more than five splits, adjusted for submergence, was just significant ($r = 0.58$, $p = 0.04$), suggesting that growth stresses within the tree may have some influence on veneer splitting.

Correlations of checking levels among discs, 1-m boards, and butt-log boards

Correlations among tree-mean values for checking in discs (except oven-dried), 1-m boards, and butt-log boards (Table 11) were all high and mostly exceeded 0.90. Checking in the 5-m boards from the butt log was highly correlated with checking in dehumidifier-dried and air- +kiln-dried boards from the 1-m billet (0.82 and 0.95 respectively), and with checking in dehumidifier-dried discs from height 6 m (0.96). However, checking in oven-dried discs correlated poorly with other checking variables and oven drying had evidently caused anomalous development of checking. Therefore, assessment of checking in dehumidifier-dried discs and in cross-sections of quarter-sawn boards from a 1-m billet (both from height 6 m), were acceptable methods of predicting checking in air-dried timber from the butt log. Non-destructive methods of assessing checking have yet to be developed.

Correlations of butt-log board collapse with shrinkage in 1-m boards and discs

Correlations among tree-mean values for collapse at the top end of the butt-log boards (Table 12) with cross-sectional area shrinkage in (adjacent) 1-m boards were moderate to

TABLE 11–Correlations among tree-mean checking in discs, 1-m boards, and butt-log boards

Variable	Oven-dried discs	Dehumidifier-dried		Air-dried		
		Discs	1-m boards	1-m boards	Butt-log boards	Butt-log boards (heart-wood)
Dehumidifier-dried discs	0.45					
Dehumidifier-dried 1-m boards	0.31	0.84 **				
Air-dried 1-m boards	0.39	0.95 **	0.90 **			
Air-dried butt-log boards	0.53	0.96 **	0.82 **	0.95 **		
Air-dried butt-log boards (heartwood)	0.20	0.90 **	0.96 **	0.93 **	0.87 **	
Kiln-dried butt-log boards (face)	0.23	0.90 **	0.94 **	0.92 **	0.81 **	0.91 **

* significant at p = 0.05
** significant at p = 0.01

strong (0.76–0.81). Correlations of butt-log board collapse score with gross radial and tangential shrinkage (without steam reconditioning) in 6-m-height disc-blocks were also moderate (0.53–0.78). Cross-sectional area shrinkage of boards from the 1-m billet was very weakly correlated with radial shrinkage of disc-blocks but moderately correlated with tangential. Collapse was not assessed in the 1-m boards. Correlations of longitudinal shrinkage with collapse, 1-m-board, and radial and tangential shrinkage were all weak and non-significant (not tabulated).

The correlation of tangential shrinkage in disc blocks with cross-sectional area shrinkage in the 1-m boards was probably reduced by use of single measurement points on the boards and discs which were affected by localised ring collapse. Shrinkage measured on 1-m boards and/or on blocks derived from discs was therefore not a very precise predictor of collapse in butt-log boards. Tangential shrinkage of disc blocks was moderately correlated (0.71) with radial shrinkage within the Rings 11–15 sample.

Correlation of checking with collapse and shrinkage

Correlations between tree means for various checking measurements with collapse and shrinkage (Table 13) indicate some interesting and useful relationships. Collapse score in the butt log was strongly correlated with checking in dehumidifier-dried and air-+kiln-dried 1-m boards, in dehumidifier-dried discs, and in the butt-log boards (0.86–0.96). Collapse is known to be closely linked to checking (Chafe *et al.* 1992), and both could be predicted in the butt-log boards from 6-m-disc and billet-board results.

Cross-sectional area shrinkage in 1-m boards (air-+kiln-dried and dehumidifier-dried) showed moderate to strong correlations with all the checking variables (0.68–0.83) and high correlations with face checking in the 5-m boards (0.88–0.91). Tangential and radial shrinkage of the outer (Rings 11–15) disc blocks correlated moderately well with most of

TABLE 12–Correlations among tree means of butt-log score and shrinkage percentage variables in unreconditioned 1-m boards and discs

Shrinkage variables	Top-end butt-log board collapse score	1-m board cross-sectional areal shrinkage (%)		Disc block shrinkage (%): rings 11–15 (from pith)		Disc block shrinkage (%): rings 1–5 (from pith)
		Air-dried	Dehumidifier-dried	Tangential	Radial	Tangential
1-m board (air-dried)	0.76*					
1-m board (dehumidifier-dried)	0.81**	0.83**				
Disc block: rings 11–15 tangential	0.75*	0.50	0.55*			
Disc block: rings 11–15 radial	0.78**	0.25	0.41	0.71**		
Disc block: rings 1–5 tangential	0.75*	0.61*	0.49	0.19	0.27	
Disc block: rings 1–5 radial	0.53	0.02	0.22	0.13	0.43	0.64*

* significant at p = 0.05
** significant at p = 0.01

TABLE 13–Correlations of butt-log collapse and unreconditioned 1-m board (6–7 m) and disc block (6 m) shrinkage variables, with checking variables

Shrinkage variables	Checking variables				
	Dehumidifier-dried disc	Dehumidifier-dried 1-m board	Air-dried 1-m board	Air-dried butt-log board	Kiln-dried butt-log board (face checks)
Butt-log board collapse	0.88 **	0.86 **	0.93 **	0.96 **	0.76 *
1-m board (air-dried)	0.73 **	0.74 **	0.68 **	0.70 *	0.91 **
1-m board (dehumidifier-dried)	0.78 **	0.83 **	0.70 **	0.78 *	0.88 **
Disc block: rings 11–15 tangential	0.77 **	0.55 *	0.67 **	0.73 *	0.68 *
Disc block: rings 11–15 radial	0.63 *	0.63 *	0.67 **	0.68 *	0.42
Disc block: rings 1–5 tangential	0.47	0.51	0.43	0.72 *	0.62
Disc block: rings 1–5 radial	0.33	0.23	0.25	0.52	0.01

* significant at p = 0.05
** significant at p = 0.01

the checking variables (0.55–0.77) but inner (Rings 1–5) tangential and radial shrinkage correlated poorly with checking. Correlations of longitudinal shrinkage with checking variables were all very low and non-significant (not tabulated).

Shrinkage has been observed to vary a lot within and between rings (as evidenced by localised collapse in boards, discs, and increment cores), and so single shrinkage points may be inadequate to estimate it. More measurements per board and per disc block may provide better correlations of mean shrinkage with checking. Cross-sectional area shrinkage from billet boards does provide some indication of propensity to checking, as do tangential and radial shrinkage measured in the outerwood of a disc. However, shrinkage is a difficult characteristic to measure and of limited value as a predictor of checking. Checking is best measured itself, on discs, as it is the product trait of economic importance. It can be easily measured on appropriately dried discs and this predicts well internal checking and face checking in butt-log boards. Tangential collapse has recently been measured successfully and extensively on 12-mm-diameter increment cores of 12-year-old *E. nitens* progenies in Tasmania, giving moderate to high heritabilities (Kube & Raymond 2002b). This method promises well for the non-destructive prediction of checking in standing trees.

Correlations among density, fibre dimensions, microfibril angle, and modulus of elasticity

As the population was selected for a range of outerwood density, correlations in this group involving 6-m-height disc and SilviScan density should be referred to as “R” rather than “r”. Correlations were moderate and positive for tree 6-m-height density with modulus of elasticity of clearwood sticks (0.53) and tree-mean modulus of elasticity of veneers (0.72) (Table 14, Fig. 8). Correlation was moderate for tree-mean modulus of elasticity of clearwood and of veneers measured sonically (0.76) (Fig. 9). Correlations of height-6-m density and SilviScan density with microfibril angle were weak and non-significant (–0.40 and –0.42 respectively). Correlation of clearwood modulus of elasticity with microfibril angle was –0.69 and of veneer modulus of elasticity with microfibril angle was –0.62. Correlation of clearwood modulus of elasticity with disc density/microfibril angle ratio was 0.81, appreciably higher than with either property individually and would be a satisfactory basis for non-destructively predicting tree modulus of elasticity from 12-mm breast-height cores. Fakopp™ sound velocity showed no significant relationship with modulus of

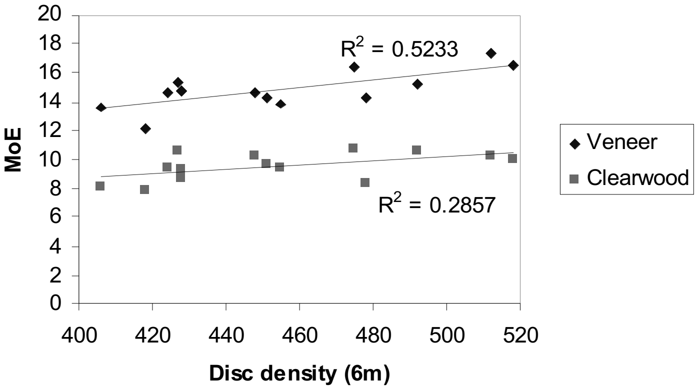

FIG. 8–Regressions of tree-mean veneer and clearwood stiffness on 6-m-height density

TABLE 14–Correlations among tree-mean clearwood and veneer modulus of elasticity, cross-sectional fibre dimensions, density, and microfibril angle

Variable	Clearwood MoE	Veneer MoE	Vessel percentage	Height 6 m disc density	SilviScan density	Radial diameter	Tangential diameter	Wall thickness	MFA
Veneer MoE	0.76 **								
Vessel percentage	–0.11	–0.02							
Height 6 m disc density	0.53 **	0.72 **	–0.39						
SilviScan density	0.58 *	0.72 **	–0.17	0.83 **					
Radial diameter	–0.27	–0.50	–0.57	–0.35	–0.62 *				
Tangential diameter	–0.25	–0.50	–0.50	–0.35	–0.67 **	0.82 **			
Wall thickness	0.62 *	0.69 **	–0.39	0.86 **	0.97 **	–0.40	–0.48		
MFA	–0.69 **	–0.62 *	–0.13	–0.40	–0.42	0.46	0.32	–0.37	
Fakopp™ velocity	–0.25	–0.10	–0.25	0.17	–0.01	0.01	0.25	0.01	0.26
Disc density/MFA ratio	0.81 **	0.77 **	–0.14	0.77 **	0.70 **	–0.47	–0.38	0.68 **	–0.88 **

* significant at p = 0.05
** significant at p = 0.01

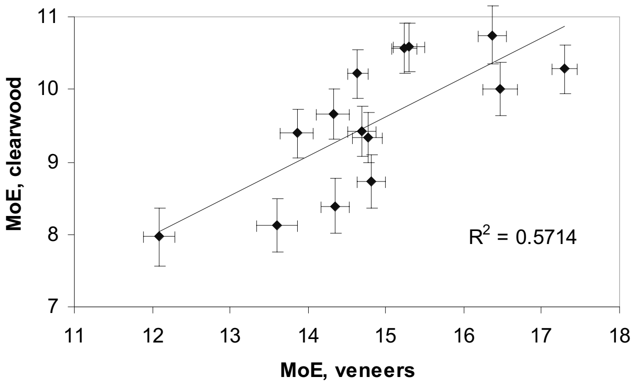

FIG. 9–Relationship between tree-mean modulus of elasticity assessed in clearwood (height 6–7 m) and veneers (height 0–13 m)

elasticity of clearwood or veneers, or with microfibril angle (or any other characteristic). Confirmation of this result is necessary in view of the difficulties and equipment failures experienced by others working with the Fakopp™ on *P. radiata*.

Of the fibre-dimension traits, wall thickness was positively correlated with modulus of elasticity (0.62) and with density from the height-6-m disc (0.86) and from SilviScan (0.97). Fibre tangential and radial diameter showed moderate negative correlations with SilviScan density (–0.62 and –0.67), but weak correlations with disc density. Clearwood and veneer modulus of elasticity were weakly and negatively correlated with fibre diameter but showed a moderate positive correlation with wall thickness, itself strongly correlated with density.

Correlations amongst clearwood mechanical properties

The correlation between tree-mean static-bending properties of modulus of elasticity and modulus of rupture was strong (0.93, Table 15), but these properties are only moderately correlated with shear and compression strength, and more strongly with hardness. Correlations between shear strength in radial and tangential directions and hardness are moderate to strong. The ability to predict modulus of elasticity from density and microfibril angle, demonstrated here and elsewhere, will thus extend to modulus of rupture and, to some extent, hardness.

TABLE 15–Correlations among tree-mean clearwood mechanical properties

Variable	MoE	MoR	Shear		Compression
			Tangential	Radial	
MoR	0.93 **				
Shear, tangential	0.41	0.66 **			
Shear, radial	0.60 *	0.71 **	0.78 **		
Compression	0.59 *	0.69 **	0.49	0.57 *	
Hardness	0.83 **	0.89 **	0.68 **	0.79 **	0.74 **

* significant at p = 0.05
** significant at p = 0.01

Correlation of growth strain, splitting, and distortion with density, fibre dimensions, microfibril angle, and modulus of elasticity

There were essentially no significant correlations at the tree-mean level between growth-strain-related sawability characteristics and density, modulus of elasticity and microfibril angle, or cell dimensions. There was some indication of a positive relationship of log splitting index with modulus of elasticity, density, and wall thickness (0.56, 0.45, 0.39) and a negative one with radial and tangential fibre diameter and microfibril angle (–0.49, –0.48, –0.56. Flitch movement off the saw was negatively correlated with fibre tangential diameter (–0.52) and log conversion percentage with density (–0.54). Neither density nor microfibril angle of individual trees was related to growth strain, based on this small (15-tree) sample.

Correlation of checking and shrinkage with density, fibre dimensions, microfibril angle, and modulus of elasticity

Neither shrinkage nor checking in 1-m boards showed any significant correlations with density at height 6 m and cross-sectional fibre dimensions, although density did show very weak correlations with checking (–0.38 to –0.42), i.e., more checking in low-density trees. This is consistent with the large species differences in checking found between 11-year-old *E. nitens* (severe checking), *E. globulus* Labill. (little checking), and *E. maidenii* Labill. (none) which paralleled densities from pith-to-bark cores of 412, 470, and 527 kg/m^3, respectively (McKinley *et al.* 2002). Correlations of checking and shrinkage with fibre dimensions and microfibril angle were all very low and non-significant.

Correlations of checking and shrinkage with growth-stress-related characteristics

Correlations of checking and shrinkage with microstrain, log splitting, and timber crook were weak and non-significant (Table 16). However, there was an appreciable positive correlation of checking and shrinkage in dehumidifier- and air-dried boards with flitch movement, and a corresponding negative relationship with log conversion and these are difficult to explain. Correlations of checking and shrinkage with veneer splitting were all very low and have not been tabulated.

Relationships between butt-log sawing and sawn timber characteristics and other variables are based on only 10 trees, while for 1-m boards and veneers 14 trees were

TABLE 16–Correlations of tree-mean checking and shrinkage in 1-m boards with butt-log sawability variables, microstrain, splitting, and distortion

Checking and shrinkage	Growth strain	Log splitting	Flitch movement	Timber crook	Log conversion
Checking: dehumidifier-dried boards	–0.07	0.00	0.56	0.21	–0.60
Checking: air-dried boards	–0.08	0.02	0.68 *	0.20	–0.56
Shrinkage: air-dried boards	0.15	0.48	0.62	0.36	–0.67 *
Shrinkage: dehumidifier-dried boards	–0.02	0.12	0.46	0.14	–0.44

* significant at p = 0.05
** significant at p = 0.01

involved, and 15 trees for other properties measured on discs. Correlations may, therefore, be affected by sampling error, especially for butt-sawlog characteristics.

Further Analyses of Variation Within and Between Trees

Sampling variation of some properties

Variance component analysis was used to quantify the between- and within-tree variance of a number of properties. Estimation of variance components has made possible the calculation of the repeatability of tree means ratio, a good index of relative variability between trees in relation to the variability of repeated measures from a single tree (Table 2), and also enabled recommendations to be made of sampling protocols for these properties.

It should be recognised that this study did not attempt to sample throughout the stem, particularly with height, for all these properties. Each tree was sampled by a butt log, then a 1-m short sawlog from 6–7 m, and veneers from the top log above. Discs were from 6 m height for assessing all properties except density. This was measured at height intervals to provide a whole-tree estimate. The sampling was dictated by the need to saw and peel a 5.5-m butt log and rotary peel the second log. The intermediate short billet and discs were therefore sited accordingly.

For some properties, within-tree variance was as large as among-tree variance. However, with the exception of spiral grain angle, sub-sampling for checking variables and clearwood modulus of elasticity reduced the within-tree variance to the extent that the repeatability of all tree means exceeded 78% and most reached or exceeded 90%. For spiral grain angle, the within-tree variance was so large that repeatability of tree means was only 23% and it was impossible to differentiate between trees. Reasonably precise tree means for all other variables could be obtained, but only by using multiple measurements for checking and modulus of elasticity. Variance components from a few of these properties were used to indicate how many samples would be required to obtain a given precision for an individual tree.

Eight boards were quarter-sawn from each tree, cut in half, then eight of them were reconditioned, four cuts were made through every board, and numbers of checks per metre of ring on each face were counted. The effects of varying the numbers of boards and cuts per board on precision were expressed in terms of the standard error, as a percentage of the mean of 5.1 checks/m of ring (Table 17). This gave a precision (standard error/mean) of

TABLE 17–Precision (standard error ÷ overall mean %) of estimates of tree-mean checking

Number of cuts per board	Number of half-boards per tree (height 6–7 m) (16 boards × 4 cuts/board)*				
	1	2	4	8	16
1	121	85	60	43	30
2	104	73	52	37	26
4	94	67	47	33	24
8	89	63	44	31	22
16	86	61	43	30	22

* Actual number of board cross-sections used to estimate “tree mean”

24%. The distribution of checking was highly positively skewed, with 66% of cuts showing no checking at all. The total variance was therefore large relative to the mean. Increasing the number of boards per tree gained more precision than increasing the number of cuts per board. An adequate level of sampling would have been four to eight boards per tree and two cuts per board.

Similar analyses were performed for outerwood density and microstrain (both at breast height), area shrinkage of 1-m boards, modulus of elasticity, and spiral grain angle (all at height 6–7 m) (Table 18). Sampling structure actually used for each property is shown in Table 18 and Fig. 2. The precision of using from 1 to 16 samples per tree at the indicated height position is expressed in terms of the standard error as a percentage of the mean. The means used were: outerwood core density 498 kg/m^3; mean shrinkage 12.4%; growth strain 537 tensile microstrain; MoE 9.57 GPa; grain angle 2.78. From this table, an appropriate number of samples at that height position might be about four for board shrinkage, two for outerwood density, four+ for growth strain, four for modulus of elasticity, and >16 for spiral grain.

TABLE 18–Precision (standard error ÷ overall mean %) of estimates of tree means for shrinkage (1-m boards), outerwood density, microstrain, modulus of elasticity, and spiral grain

No. of measurements	Shrinkage (8 × 1-m boards height 6–7 m)*	Outerwood density (4 × breast height core)	Tensile microstrain (2 × breast height)	MOE (4 sticks × 2 sides height 6–7 m)	Spiral grain angle (approx. seven rings from disc height 6 m)
1	11.8	3.9	41.1	10.9	102
2	8.3	2.8	29.0	7.7	72
4	5.9	2.0	20.5	5.4	51
8	4.2	1.4	14.5	3.8	36
16	3.0	1.0	10.3	2.6	25

*Actual number of samples used for estimating "tree means" in the study

Variation in modulus of elasticity of veneer, from pith to bark

The diameter of the peeler log at point of peeling was reconstructed as veneer sheets were identified in the peeling sequence. ANOVA was used to examine the variation in modulus of elasticity within and among trees (Table 19). Veneer sheet modulus of elasticity within the tree increased over two-fold from pith to bark (Fig.10). This is shown in the ANOVA by the strong effect of log diameter at point of peeling. The effect is slightly but significantly nonlinear, as shown by the quadratic and cubic terms in the ANOVA. Variation due to height, i.e., first and second peeler bolts from the butt log and first and second peeler bolts from second log, was also highly significant (Fig. 10), as were tree-to-tree differences. Veneer stiffness was lowest for the basal bolt from the butt log (height 1.0 m) and increased substantially for the second bolt (height 3 m) and again for first and second bolts from the second log (heights 7 and 9 m). Veneer modulus of elasticity values were measured dynamically from sound velocity which gives values about 1.9 times higher than those from static bending, as in Fig. 10 (R.E.Booker unpubl. data).

TABLE 19–Analysis of covariance of veneer modulus of elasticity

Source	DF	MS	F-ratio	p-value
Log diameter	1	1711.1	1768.52	<0.0001
(Log diameter)^2	1	2.5	2.64	0.105
(Log diameter)^3	1	91.0	94.14	<0.0001
Tree	13	75.6	78.20	<0.0001
Log diameter × tree	13	13.1	13.62	<0.0001
Height	3	152.0	157.15	<0.0001
Diameter × height	3	22.2	23.03	0.016
Height × tree	21	12.7	13.21	<0.0001
Residual	598	59.1		

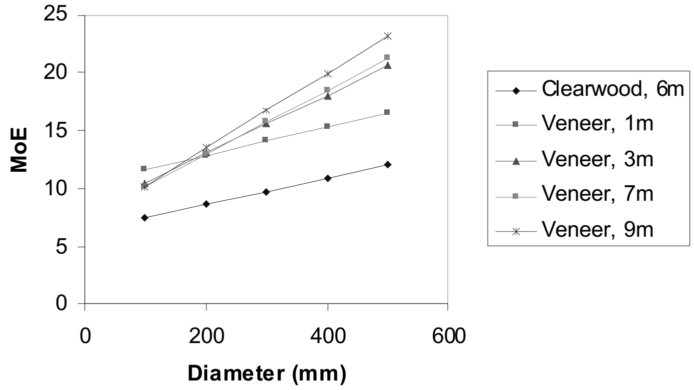

FIG. 10–Relationship of veneer dynamic modulus of elasticity (sonic determination) to diameter at point of peeling, for increasing billet heights, *vs* static bending modulus of elasticity of clearwood at height 6 m

As discussed earlier, overall mean basic density decreased from 497 kg/m^3 at the base of the butt log (Table 6) to 475 kg/m^3 at height 6 m. From there, it started to increase, to 494 kg/m^3 at height 10 m up to 572 kg/m^3 at 30 m. Density is positively correlated with modulus of elasticity, so veneer modulus of elasticity could be expected to decrease with height, at least within the butt log up to height 6 m. However, the modulus of elasticity of veneer increased within the butt log (Fig. 10) and continued to increase within the second log, despite the decrease in density up to height 6 m. It seems likely that the increase in veneer modulus of elasticity with height might be due to a decrease in microfibril angle with height, as well as the increase in density above 6 m. In this study, microfibril angle has only been measured by SilviScan at height 6 m. By similar reasoning, the values of clearwood modulus of elasticity from height 6–7 m, discussed below, were likely to be higher than in the butt log. This was indicated in a study of 29 trees of 16-year-old *E. nitens* from Kaingaroa Forest (Evans *et al.* 2000) where microfibril angle showed a rapid reduction from base up to height 6 m, thereafter stabilising but eventually increasing above 16 m.

Within- and among-tree variation of clearwood strength and stiffness properties

Variation in clearwood modulus of elasticity among the eight test sticks from 1-m billets, four each from north and south sides, was examined by ANOVA (Table 20). There

TABLE 20–Analysis of covariance for clearwood modulus of elasticity

Source	DF	MS	F-ratio	p-value
Stem diameter	1	285.24	310.25	<0.0001
(Stem diameter)^2	1	10.19	11.08	0.001
(Stem diameter)^3	1	4.50	4.90	0.033
North/south direction	1	2.70	2.95	0.090
Tree	13	6.04	6.57	<0.0001
Residual	86	0.919		

was an extremely significant effect on modulus of elasticity due to distance from the pith, as "stem diameter" (as well as significant quadratic and cubic "diameter" effects similar to the veneers), and significant differences among trees, but differences in modulus of elasticity between north and south sides of the stem were not significant. This reflected the substantial increase in modulus of elasticity that occurred from pith to bark. The overall mean clearwood modulus of elasticity values, determined by mechanical testing, were much lower than modulus of elasticity values of veneer, determined sonically at corresponding distances from the pith, and increased more slowly from pith to bark than veneer values (Fig. 10).

The predicted means for radial positions from pith to bark showed a steep gradient from pith to bark for modulus of elasticity, modulus of rupture, and hardness (Table 8). The variance components (Table 21) for variance among trees, among radial positions within trees (four equidistant points, pith to bark), and within radial positions (two sticks from opposite radii) showed clearly what a large part of the total variance was accounted for by radial position from pith to bark, particularly for modulus of elasticity and modulus of rupture (68% and 78% respectively). Variation among trees occupied a very small part of total test stick variance of these two properties (1% and 7% respectively). Variance due to radial position was less important for compression strength and hardness. Correspondingly, between-tree variation was much more important for these properties and so was circumferential variation within radial position (not a lot of variation from pith to bark).

TABLE 21–Variance components from nested analyses of variance of mechanical properties

Property	Variance component estimates		
	Among trees	Among radial positions within trees	Within radial position, within trees
MoE (GPa)	0.059	3.496	0.908
MoR (MPa)	17.0	177.8	68.4
Shear, tangential (MPa)	0.85	0.41	0.89
Shear, radial (MPa)	1.44	1.42	5.04
Compression (MPa)	8.86	18.98	16.17
Hardness (N)	95 000	449 000	514 000

Association between modulus of elasticity, density, and microfibril angle

There were strong relationships between modulus of elasticity, density, and microfibril angle for the individual test sticks cut from the 1-m billet. Modulus of elasticity and nominal density were measured for each sample stick, but a value of microfibril angle had to be obtained by interpolation of the SilviScan data (from the height 6 m disc) at the corresponding radial position of each sample. The correlations at the individual stick level between modulus of elasticity and nominal density (r = 0.86, n = 103) and between modulus of elasticity and microfibril angle (r = –0.79) were both highly significant. The following multiple regression in which both variables were highly significant, was fitted:

$$\text{MoE} = 1.77\ (1.04) + 0.0219\ (0.0015)\ \text{Density} - 0.218\ (0.022)\ \text{MFA}$$

$R^2 = 0.87$ (standard errors of partial regression coefficients in parentheses)

A quadratic microfibril angle term was tested, and was non-significant. Sample radial position was added to the regression model but it gave no significant improvement in fit. Separate intercepts were then fitted for each tree. These gave a small, but only marginally significant improvement in fit (p = 0.04). The interaction term between density and microfibril angle was not significant. The partial correlation of modulus of elasticity on microfibril angle at constant density was –0.71, and for modulus of elasticity with density at constant microfibril angle was 0.82. The lack of a response in R^2 to adding radial position to the regression suggests that density and microfibril angle can fully explain the strong within-tree gradient of individual stick modulus of elasticity with increasing distance from the pith (Fig. 6 and 10). However, this gradient in modulus of elasticity is probably more closely related to microfibril angle, which decreased strongly from pith to bark (Fig. 7), than to density which showed little radial trend (Fig. 5). This suggests that between-tree variation in modulus of elasticity in *E. nitens* can also be largely explained in terms of density and microfibril angle (as is indicated in the correlation for tree means of 0.81 of modulus of elasticity with density/microfibril angle, Table 14).

GENERAL DISCUSSION

There were two main objectives of this 15-individual-tree study of *Eucalyptus nitens*. The first, covered by McKenzie *et al.* (2003), was to evaluate a fast-grown, pruned stand of this species for its production of appearance-grade lumber and structural veneer, from pruned butt logs and from butt and second logs, respectively. The second objective, in this paper, was to develop methods for predicting quality and yield of these solid-wood products, non-destructively from increment cores and measurements on the standing tree, and destructively from discs and a short billet. Characterising variation within and among individual trees in properties of logs, sawn timber, and veneer, and basic wood properties, and their inter-relationships indicated some of the causes of variation in end-product characteristics. It also showed ways of predicting sawn-timber and veneer quality and yield from wood properties. Quantifying variability between trees in different traits also indicated potential for their genetic improvement.

Tree growth was very rapid in the study trees, and timely pruning had adequately restricted the size of the knotty core. Longitudinal growth stress, as measured by microstrain at breast height, varied widely between trees and was the apparent cause of end-splitting of logs. Trees varied in end-splitting, and ranked similarly for butt- and second-log splitting. The worst-affected tree could not be peeled because of large end-splits. Varying amounts of flitch movement were recorded when the first saw-cut was made. There were varying amounts of crook in boards cut from the flitches, and its removal reduced timber conversion.

Slow air-drying of the lumber, followed by kiln-drying and steam reconditioning (and cross-cutting in half and ripping to remove crook, wane, and knots) resulted in straight boards with no bow or twist. However, the two main drying defects, collapse and checking, severely reduced the quality of the lumber. Unacceptable levels of collapse occurred in two trees out of 10 and collapse was far worse at the bottom end of the butt-log boards than at the top. Internal checking, assessed after air-drying, was widespread in butt-log boards, in 1-m boards from height 6–7 m, and in discs from height 6 m, but frequency was highly variable between trees. Face checks, assessed in butt-log boards after kiln drying and steam reconditioning, occurred in boards of all 10 trees.

Recovery of veneer volume as a percentage of log volume averaged 56% (excluding one unpeeled log), varying widely among trees. Thickness of veneer sheets varied unacceptably, but this reflected mainly insufficient development work on knife setting for rotary peeling. Uneven preheating of the logs to plasticise the wood for peeling was blamed as at least part of the cause of excessive veneer splitting. Veneer sheet stiffness, measured individually by Pundit™, was also highly variable within and among trees, and use of this equipment enabled effective sorting of veneers into stiffness classes for manufacture and testing of laminated veneer lumber (LVL) (Gaunt *et al.* 2003).

For "sawability" (i.e., end-splitting of logs, flitch movement in the first saw-cuts, crook in boards, and timber conversion) the measurement of microstrain from only two breast-height measurements per tree could predict tree means of these characteristics. Longitudinal growth stresses are the most serious problem that affects utilisation of hardwoods for sawn timber and they are particularly bad for most eucalypt species. Applying the well-known Nicholson (1971) method is a practical way of comparing individual trees of different species in the search for species that are less seriously affected.

There was a high correlation of checking and collapse in air-dried butt-log boards with checking in dehumidifier-dried (but not oven-dried) discs and 1-m boards (both from height 6 m). Thus butt-log drying defects could be predicted without sawing the butt log. Other studies have shown a rapid decrease in checking frequency from base of trees of *E. nitens* up to height 11 m (Shelbourne *et al.* 2002).

Tree mean collapse in butt-log boards was moderately correlated with cross-sectional area shrinkage of 1-m boards and with outerwood tangential shrinkage from the 6-m-height disc blocks. Collapse in the 1-m boards was unfortunately not assessed, but should correlate well with collapse in the butt log. Collapse (and shrinkage) has now been successfully measured on breast height increment cores (Kube *et al.* 2001) and this would be a valuable non-destructive means of predicting collapse and checking.

Tree mean mechanical properties of clearwood, particularly modulus of elasticity, (from the billet at 6–7 m height), could be predicted by the density/microfibril angle ratio ($r = 0.81$). Tree-mean modulus of elasticity was estimated from eight test sticks while tree-mean microfibril angle and density were determined by SilviScan from a single pith-to-bark strip at height 6 m, but a breast-height 12-mm core could equally well be used. The modulus of elasticity of individual test sticks was related to their nominal density and to microfibril angle in that ring. A multiple regression of single test-stick modulus of elasticity, with density and microfibril angle as independent variables, explained 87% of the total variation of test-stick modulus of elasticity. However, the variation of test-stick modulus of elasticity was largely due to pith-to-bark radial position and only 1.3% of total variance in modulus of elasticity was accounted for by differences among trees. Microfibril angle determined much of the pith to bark gradient in modulus of elasticity.

Tree-mean modulus of elasticity of veneer sheets, measured sonically by Pundit™, correlated moderately well with modulus of elasticity of clearwood (0.77) and similarly with density, microfibril angle, and density/microfibril angle ratio. Evaluating or selecting trees for stiffness of veneer would also be feasible through breast height pith-to-bark cores. Veneer splitting, however, was unrelated to other properties.

CONCLUSIONS

In summation, in *E. nitens* growth stress determines log end-splitting and sawability characteristics, which seem to be independent of all others. Internal checking and collapse, principal drying defects of sawn timber, are themselves closely related, and moderately correlated with tangential shrinkage, but are independent of other characteristics. At the tree-mean level, modulus of elasticity of both clearwood and veneer is moderately correlated with density and with microfibril angle (and more strongly with the microfibril angle/density ratio), but is independent of checking and collapse, and of growth-stress-related characteristics. Cross-sectional fibre dimensions did not show any relationship to solid-wood properties.

Large within-tree variability is a feature of most of the sawing, lumber, and basic wood properties of *E. nitens*, as well as large among-tree variation. Repeatability of tree-mean values for most traits can be increased to over 70% by ensuring sufficient sub-samples per tree. The large among-tree variability in important sawability and sawn-timber defects suggests that some or even much of this variation may be genetically controlled.

Species, populations, and individual trees can be characterised satisfactorily by measurements of growth stresses made on the standing tree (though these may be destructive); of log end-splits; and of checking, collapse, and mechanical properties, from increment cores, from discs, and from boards sawn from a short billet. This can be done without recourse to full-scale sawing studies. Increment cores, taken at breast height, are a promising means of non-destructive evaluation of checking, collapse, density, and microfibril angle, and thus of modulus of elasticity.

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